AFRL-AFOSR-VA-TR-2016-0178

Laboratory Experiments to Simulate and Investigate

Paul Bellan
CALIFORNIA INSTITUTE OF TECHNOLOGY

05/12/2016
Final Report

Air Force Research Laboratory
AF Office Of Scientific Research (AFOSR)/ RTB1
Arlington, Virginia 22203
Air Force Materiel Command

REPORT DOCUMENTATION PAGE	*Form Approved OMB No. 0704-0188*

1. REPORT DATE *(DD-MM-YYYY)*	**2. REPORT TYPE**	**3. DATES COVERED** *(From - To)*
06-05-2016	Final	08-01-2011 to 07-31-2016

4. TITLE AND SUBTITLE
LABORATORY EXPERIMENTS TO SIMULATE AND INVESTIGATE THE PHYSICS UNDERLYING THE DYMANICS OF MERGING SOLAR CORONA STRUCTURES

5a. CONTRACT NUMBER

5b. GRANT NUMBER
FA9550-11-1-0184

5c. PROGRAM ELEMENT NUMBER

6. AUTHOR(S)
Bellan, Paul M.

5d. PROJECT NUMBER

5e. TASK NUMBER

5f. WORK UNIT NUMBER

7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES)
California Institute of Technology
1200 E. California Blvd.
Pasadena CA 91125

8. PERFORMING ORGANIZATION REPORT NUMBER

9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES)
Dr. Julie J Moses
Program Officer, Space Sciences
Air Force Office of Scientific Research
875 N Randolph St Suite 3000
Arlington, VA 22203

10. SPONSOR/MONITOR'S ACRONYM(S)
AFOSR

11. SPONSOR/MONITOR'S REPORT NUMBER(S)

12. DISTRIBUTION/AVAILABILITY STATEMENT
For unlimited public distribution

13. SUPPLEMENTARY NOTES

14. ABSTRACT
The research program has used laboratory experiments and theoretical models to investigate MHD equilibria relevant to solar and space physics, dynamical behavior at the MHD scale (i.e., motion, deformation, and topological changes of the macroscopic structure such as expansion of a solar corona loop), MHD instabilities (e.g., kink and Rayleigh-Taylor instabilities), high frequency waves that are generated by transients associated with the instabilities (e.g., generation of whistler waves), particle energization (e.g., electron and ion heating, changes in ionization state, emission of energetic photons), complex particle orbits in an electro-magnetic field (e.g., extension of adiabatic invariant concepts, stochastic heating, Hamiltonian concepts, relativistic particle motion in a circularly polarized wave), and new diagnostic techniques (e.g., coded aperture imaging, determining wave-vector k from single spacecraft measurements). Thirteen papers have been published in scientific journals and one additional paper has just been submitted.

15. SUBJECT TERMS
solar physics, plasma physics, eruptions from the solar corona, MHD instabilities, waves, heating, diagnostic methods, magnetohydrodynamics, whistler waves, MHD jets

16. SECURITY CLASSIFICATION OF: a. REPORT	b. ABSTRACT	c. THIS PAGE	**17. LIMITATION OF ABSTRACT**	**18. NUMBER OF PAGES**	**19a. NAME OF RESPONSIBLE PERSON**
U	U	U	UU	1	Paul M. Bellan
					19b. TELEPHONE NUMBER *(Include area code)* 626-395-4827

Reset

Standard Form 298 (Rev. 8/98)
Prescribed by ANSI Std. Z39.18
Adobe Professional 7.0

INSTRUCTIONS FOR COMPLETING SF 298

1. REPORT DATE. Full publication date, including day, month, if available. Must cite at least the year and be Year 2000 compliant, e.g. 30-06-1998; xx-06-1998; xx-xx-1998.

2. REPORT TYPE. State the type of report, such as final, technical, interim, memorandum, master's thesis, progress, quarterly, research, special, group study, etc.

3. DATES COVERED. Indicate the time during which the work was performed and the report was written, e.g., Jun 1997 - Jun 1998; 1-10 Jun 1996; May - Nov 1998; Nov 1998.

4. TITLE. Enter title and subtitle with volume number and part number, if applicable. On classified documents, enter the title classification in parentheses.

5a. CONTRACT NUMBER. Enter all contract numbers as they appear in the report, e.g. F33615-86-C-5169.

5b. GRANT NUMBER. Enter all grant numbers as they appear in the report, e.g. AFOSR-82-1234.

5c. PROGRAM ELEMENT NUMBER. Enter all program element numbers as they appear in the report, e.g. 61101A.

5d. PROJECT NUMBER. Enter all project numbers as they appear in the report, e.g. 1F665702D1257; ILIR.

5e. TASK NUMBER. Enter all task numbers as they appear in the report, e.g. 05; RF0330201; T4112.

5f. WORK UNIT NUMBER. Enter all work unit numbers as they appear in the report, e.g. 001; AFAPL30480105.

6. AUTHOR(S). Enter name(s) of person(s) responsible for writing the report, performing the research, or credited with the content of the report. The form of entry is the last name, first name, middle initial, and additional qualifiers separated by commas, e.g. Smith, Richard, J, Jr.

7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES). Self-explanatory.

8. PERFORMING ORGANIZATION REPORT NUMBER. Enter all unique alphanumeric report numbers assigned by the performing organization, e.g. BRL-1234; AFWL-TR-85-4017-Vol-21-PT-2.

9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES). Enter the name and address of the organization(s) financially responsible for and monitoring the work.

10. SPONSOR/MONITOR'S ACRONYM(S). Enter, if available, e.g. BRL, ARDEC, NADC.

11. SPONSOR/MONITOR'S REPORT NUMBER(S). Enter report number as assigned by the sponsoring/ monitoring agency, if available, e.g. BRL-TR-829; -215.

12. DISTRIBUTION/AVAILABILITY STATEMENT. Use agency-mandated availability statements to indicate the public availability or distribution limitations of the report. If additional limitations/ restrictions or special markings are indicated, follow agency authorization procedures, e.g. RD/FRD, PROPIN, ITAR, etc. Include copyright information.

13. SUPPLEMENTARY NOTES. Enter information not included elsewhere such as: prepared in cooperation with; translation of; report supersedes; old edition number, etc.

14. ABSTRACT. A brief (approximately 200 words) factual summary of the most significant information.

15. SUBJECT TERMS. Key words or phrases identifying major concepts in the report.

16. SECURITY CLASSIFICATION. Enter security classification in accordance with security classification regulations, e.g. U, C, S, etc. If this form contains classified information, stamp classification level on the top and bottom of this page.

17. LIMITATION OF ABSTRACT. This block must be completed to assign a distribution limitation to the abstract. Enter UU (Unclassified Unlimited) or SAR (Same as Report). An entry in this block is necessary if the abstract is to be limited.

Final Report: "LABORATORY EXPERIMENTS TO SIMULATE AND INVESTIGATE THE PHYSICS UNDERLYING THE DYMANICS OF MERGING SOLAR CORONA STRUCTURES" AFOSR Grant FA9550-11-1-0184 (August 1, 2011 to July 31, 2016)

Principal Investigator: Professor Paul M. Bellan
Applied Physics and Materials Science
California Institute of Technology
Pasadena, CA 91125
pbellan@caltech.edu
626-395-4827

May 6, 2016

The solar corona is largely governed by the physics of plasmas and this physics has many different scales ranging from macroscopic MHD scales to microscopic particle orbit scales. There are also many different time scales ranging from steady-state equilibria to the very short periods of high frequency plasma waves. While these different space and time scales have been individually studied in the past, it is now realized that real-world physics typically involves substantial interaction between the different space and time scales. The dynamics of the solar corona is of particular interest because structures that are either static or have slowly built up to their present state can suddenly erupt and eject magnetized plasmas into interplanetary space while simulateously spewing out energetic charged particles and radiating waves over a wide range of frequencies. Studying this complex behavior requires understanding equilibria, destabilization of equilibria, and transient phenomena having a great range of length and time scales.

Plasma equations such as magnetodrodynamics, two fluid, or Vlasov have no intrinsic scale and so, in principle, phenomena occurring in the solar corona

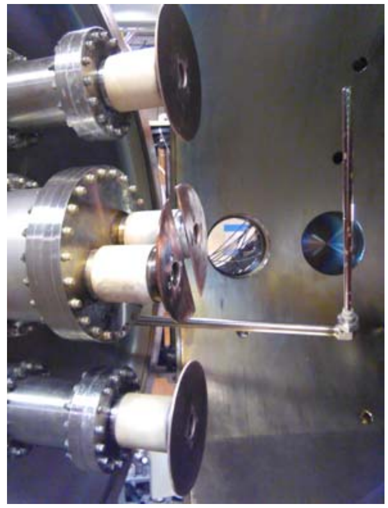

Figure 1: Electrode system used to make a pair of interacting MHD-driven plasma loops. Stalk on right is a magnetic probe array.

could also occur in laboratory experiments providing the appropriate boundary conditions are imposed. Such experiments are being implemented at Caltech. The experiments are not exact scale models but nevertheless provide useful qualitative insights because they are governed by the same dynamical relationships, have similar morphology, and often reveal the linkage between phenomena having widely separated length and time scales.

The laboratory experiments simulate coronal loop structures, MHD-driven jets, and manifest many of the MHD, microscopic, dynamical, wave and particle phenomena associated with solar physics. A typical electrode setup for making lab-scale versions of solar corona loops is shown in Fig. 1 while Fig.2 shows photos of actual plasma superimposed on the electrodes. During the last two years a new set of magnetic probes has been constructed that provides unprecedented space and time resolution so that the magnetic field, the current density, and the resulting MHD force vectors are measured in a three dimensional volume and then related to the observed motion. Figure 3 shows an example of the magnetic field measurements while Fig.4 shows measurements of the electric current density. These measurements allow direct calculation of the $\mathbf{J} \times \mathbf{B}$ force and show that the plasma has bulk motion consistent with this force.

The research program has investigated MHD equilibria relevant to solar and space physics, dynamical behavior at the MHD scale (i.e., motion, deformation, and topological changes of the macroscopic structure such as expansion of a solar corona loop), MHD instabilities (e.g., kink and Rayleigh-Taylor instabilities), high frequency waves that are generated by transients associated with the instabilities (e.g., generation of whistler waves), particle energization (e.g., elec-

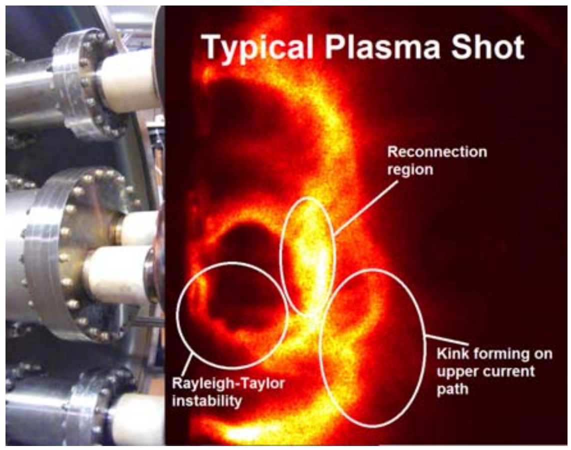

Figure 2: Photo of plasma superimposed on electrode structure.

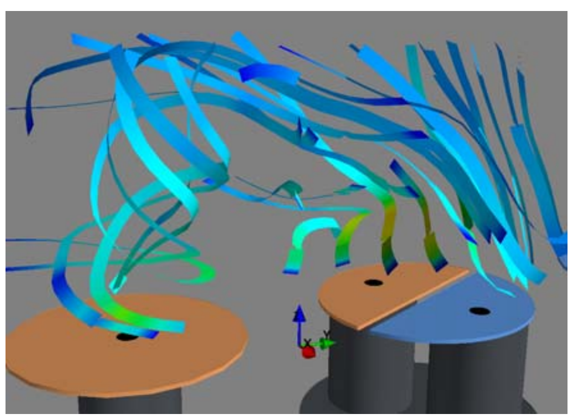

Figure 3: Experimentally measured magnetic field.

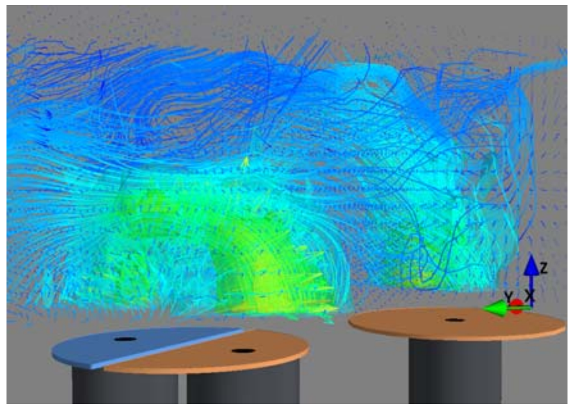

Figure 4: Experimentally measured current density.

tron and ion heating, changes in ionization state, emission of energetic photons), complex particle orbits in an electro-magnetic field (e.g., extension of adiabatic invariant concepts, stochastic heating, Hamiltonian concepts, relativistic particle motion in a circularly polarized wave), and new diagnostic techniques (e.g., coded aperture imaging, determining wave-vector $\mathbf{k}(\omega)$ from single spacecraft measurements).

The results have been published in the scientific literature and presented at conferences. Fourteen papers have been published during 2011-2016 or are have been submitted (titles and journals are given in the list of references at the end of this report). Below are brief summaries of each paper. These summaries show how the research program has investigated behavior at many different length and time scales as well as the interaction between these varied scales.

1. Stenson & Bellan (2012) showed that the plasma coming from each footpoint of a coronal loop is actually a jet driven by MHD forces.
2. Bellan (2012) showed that the dispersion relations for magnetized warm plasma waves could be derived more efficiently by using current density rather than electric field as the fundamental wave quantity.
3. Moser & Bellan (2012) showed that the effective gravity produced by the lateral acceleration of a kink instability provides the environment for a fast growing Rayleigh-Taylor instability; thus there is a cascade from one type of MHD instability (kink) to another faster and finer-scale instability (Rayleigh-Taylor). This shows how one scale affects another.
4. Bellan (2013a) provided a new and simple derivation showing that the magnetic field of a whistler wave is circularly polarized even when the wave k-vector is not parallel to the background magnetic field whereas the wave electric field is only circularly polarized for parallel propagation.

5. Bellan (2013b) showed that a relativistic electron interacting with a low amplitude circularly polarized electromagnetic wave (e.g., whistler) propagating in a magnetized plasma undergoes extremely strong pitch angle scattering.

6. Chaplin & Bellan (2013) described a fast trigger circuit for ignitron high power electric switch tubes such as used in our experiments. This trigger circuit uses IGBT devices

7. Bellan (2014) showed that fast non-MHD reconnection involves coupling between out-of-plane electric and magnetic fields and that the coupled equations are generalizations of the equations that produce whistler waves when the plasma is uniform. This shows that whistler physics is intimately related to fast reconnection.

8. Bellan *et al.* (2015) provided an overview of the experimental activities by the Bellan plasma group at Caltech. This paper was chosen to be a featured article by the Journal of Plasma Physics and given free distribution.

9. Bellan & Paccagnella (2015) described analytic Grad-Shafranov toroidal equilibria where the pressure on the magnetic axis is lower than the pressure external to the toroid so there is effectively a magnetic bubble. This is relevant to interplanetary magnetic clouds spawned by the eruptions of solar corona structures.

10. Perkins & Bellan (2015) analyzed orbit-averaged particle motion using Hamiltonian methods and showed how orbit-averaged quantities such as the flux enclosed by an orbit could be calculated from operations on the action integral.

11. Haw & Bellan (2015) described implementation of a coded aperature imaging system that provided high-speed images of a plasma jet without using lenses or mirrors.

12. Chai *et al.* (2016) described a set of interrelated experimental measurements that resolved the sequence of an MHD kink instability of a jet spawning a Rayleigh-Taylor instability that in turn spawned what is presumed to be a magnetic reconnection. Electron and ion heating as well of whistler wave radiation were observed in conjunction with the magnetic reconnection. The circular polarization of the whistler wave was observed. This paper was selected to be an Editor's Pick by the editor of the Physics of Plasmas. This paper illustrates a cascade of scales: MHD flow $\Rightarrow$ MHD kink instability $\Rightarrow$ MHD Rayleigh-Taylor instability $\Rightarrow$ reconnection $\Rightarrow$ whistler wave emission, particle energization.

13. Zhai & Bellan (2016) provided a semi-analytic model for the Rayleigh-Taylor instability resulting from the lateral acceleration of a cylindrical plasma such as a kinked jet or an accelerating coronal loop.

14. Bellan (2016) is a just-submitted manuscript to JGR-Space Physics showing how the wave-vector $\mathbf{k}(\omega)$ of a traveling wave can be determined from single-spacecraft measurements of the wave magnetic field $\mathbf{B}(t)$ and the wave current density $\mathbf{J}(t)$.

Paul Bellan and/or members of his group have attended and made presentations at the annual APS Division of Plasma Physics Meeting, the bi-annual High Energy Laboratory Astrophysics meeting, the AFOSR Space Science Program Review, the SHINE solar physics meeting, the International Astrophysics Conference, and the workshop "Complex plasma phenomena in the laboratory and in the universe".

References

Bellan, P. M. 2012. Improved basis set for low frequency plasma waves. *Journal of Geophysical Research-Space Physics*, **117**. A12219.

Bellan, P. M. 2013a. Circular polarization of obliquely propagating whistler wave magnetic field. *Physics of Plasmas*, **20**(8). 082113.

Bellan, P. M. 2013b. Pitch angle scattering of an energetic magnetized particle by a circularly polarized electromagnetic wave. *Physics of Plasmas*, **20**(4). 042117.

Bellan, P. M. 2014. Fast, purely growing collisionless reconnection as an eigenfunction problem related to but not involving linear whistler waves. *Physics of Plasmas*, **21**. 102108.

Bellan, P. M. 2016. Revised Single-Spacecraft Method for Determining Wavevector k and Resolving Space-time Ambiguity. *GR-Space Physics*. submitted.

Bellan, P. M., Zhai, X., Chai, K. B., & Ha, B. N. 2015. Complex astrophysical experiments relating to jets, solar loops, and water ice dusty plasma. *Journal of Plasma Physics*, **81**. 495810502.

Bellan, Paul M., & Paccagnella, Roberto. 2015. Magnetic axis safety factor of finite beta spheromaks and transition from spheromaks to toroidal magnetic bubbles. *Physics of Plasmas*, **22**(2).

Chai, K.B., Zhai, X., & Bellan, P. M. 2016. Extreme ultra-violet burst, particle heating, and whistler wave emission in fast magnetic reconnection induced by kink-driven Rayleigh-Taylor instability. *Physics of Plasmas*, **23**. 032122.

Chaplin, Vernon H., & Bellan, Paul M. 2013. Fast Ignitron Trigger Circuit Using Insulated Gate Bipolar Transistors. *IEEE Transactions on Plasma Science*, **41**(4), 975–979.

Haw, Magnus, & Bellan, Paul. 2015. 1D fast coded aperture camera. *Review of Scientific Instruments*, **86**(4). 043506.

Moser, Auna L., & Bellan, Paul M. 2012. Magnetic reconnection from a multi-scale instability cascade. *Nature*, **482**(7385), 379–381.

Perkins, R. J., & Bellan, P. M. 2015. Orbit-averaged quantities, the classical Hellmann-Feynman theorem, and the magnetic flux enclosed by gyro-motion. *Physics of Plasmas*, **22**(2). 022108.

Stenson, E. V., & Bellan, P. M. 2012. Magnetically Driven Flows in Arched Plasma Structures. *Physical Review Letters*, **109**(7). 075001.

Zhai, X., & Bellan, P. M. 2016. A hybrid Rayleigh-Taylor-current-driven coupled instability in a magnetohydrodynamically collimated cylindrical plasma with lateral gravity. *Physics of Plasmas*, **23**. 032121.

1.

1. Report Type

Final Report

Primary Contact E-mail
Contact email if there is a problem with the report.

pbellan@caltech.edu

Primary Contact Phone Number
Contact phone number if there is a problem with the report

626-395-4827

Organization / Institution name

California Institute of Technology

Grant/Contract Title
The full title of the funded effort.

LABORATORY EXPERIMENTS TO SIMULATE AND INVESTIGATE THE PHYSICS UNDERLYING THE DYMANICS OF MERGING SOLAR CORONA STRUCTURES

Grant/Contract Number
AFOSR assigned control number. It must begin with "FA9550" or "F49620" or "FA2386".

FA9550-11-1-0184

Principal Investigator Name
The full name of the principal investigator on the grant or contract.

Paul Murray Bellan

Program Manager
The AFOSR Program Manager currently assigned to the award

Julie J. Moses

Reporting Period Start Date

08/01/2011

Reporting Period End Date

07/31/2016

Abstract

The research program has used laboratory experiments and theoretical models to investigate MHD equilibria relevant to solar and space physics, dynamical behavior at the MHD scale (i.e., motion, deformation, and topological changes of the macroscopic structure such as expansion of a solar corona loop), MHD instabilities (e.g., kink and Rayleigh-Taylor instabilities), high frequency waves that are generated by transients associated with the instabilities (e.g., generation of whistler waves), particle energization (e.g., electron and ion heating, changes in ionization state, emission of energetic photons), complex particle orbits in an electro-magnetic field (e.g., extension of adiabatic invariant concepts, stochastic heating, Hamiltonian concepts, relativistic particle motion in a circularly polarized wave), and new diagnostic techniques (e.g., coded aperture imaging, determining wave-vector k from single spacecraft measurements).

In one set of experiments a fast MHD-driven plasma jet undergoes a kink instability which causes the plasma to form a fast growing corkscrew end. The lateral acceleration associated with this growth produces an effective gravity that provides the environment for an even faster Rayleigh-Taylor instability. The Rayleigh-Taylor instability instigates what is believed to be a magnetic reconnection. Rapid particle heating and emission of whistler waves is observed in association with whistler emission.

In another set of experiments a magnetic probe array has been used to map out the 3D magnetic field of a loop-like plasma with sufficient resolution to allow calculation of the current density J from the curl of the magnetic field.

Distribution Statement

This is block 12 on the SF298 form.

Distribution A - Approved for Public Release

Explanation for Distribution Statement

If this is not approved for public release, please provide a short explanation. E.g., contains proprietary information.

SF298 Form

Please attach your SF298 form. A blank SF298 can be found here. Please do not password protect or secure the PDF The maximum file size for an SF298 is 50MB.

AFD-070820-035-Bellan.pdf

Upload the Report Document. File must be a PDF. Please do not password protect or secure the PDF . The maximum file size for the Report Document is 50MB.

afosr-final-report-2016-v5.pdf

Upload a Report Document, if any. The maximum file size for the Report Document is 50MB.

Archival Publications (published) during reporting period:

Bellan, P. M. 2012. Improved basis set for low frequency plasma waves. Journal of Geophysical Research-Space Physics, 117. A12219.

Bellan, P. M. 2013a. Circular polarization of obliquely propagating whistler wave magnetic field. Physics of Plasmas, 20(8). 082113.]

Bellan, P. M. 2013b. Pitch angle scattering of an energetic magnetized particle by a circularly polarized electromagnetic wave. Physics of Plasmas, 20(4). 042117.

Bellan, P. M. 2014. Fast, purely growing collisionless reconnection as an eigenfunction problem related to but not involving linear whistler waves. Physics of Plasmas, 21. 102108.

Bellan, P. M., Zhai, X., Chai, K. B., & Ha, B. N. 2015. Complex astrophysical experiments relating to jets, solar loops, and water ice dusty plasma. Journal of Plasma Physics, 81. 495810502.

Bellan, Paul M., & Paccagnella, Roberto. 2015. Magnetic axis safety factor of finite beta spheromaks and transition from spheromaks to toroidal magnetic bubbles. Physics of Plasmas, 22(2).

Chai, K.B., Zhai, X., & Bellan, P. M. 2016. Extreme ultra-violet burst, particle heating, and whistler wave emission in fast magnetic reconnection induced by kink-driven Rayleigh-Taylor instability. Physics of Plasmas, 23. 032122.

Chaplin, Vernon H., & Bellan, Paul M. 2013. Fast Ignitron Trigger Circuit Using Insulated Gate Bipolar Transistors. IEEE Transactions on Plasma Science, 41(4), 975—979.

Haw, Magnus, & Bellan, Paul. 2015. 1D fast coded aperture camera. Review of Scientific Instruments, 86(4). 043506.

Moser, Auna L., & Bellan, Paul M. 2012. Magnetic reconnection from a multiscale instability cascade. Nature, 482(7385), 379—381.

Perkins, R. J., & Bellan, P. M. 2015. Orbit-averaged quantities, the classical Hellmann-Feynman theorem, and the magnetic flux enclosed by gyro-motion. Physics of Plasmas, 22(2). 022108.

Stenson, E. V., & Bellan, P. M. 2012. Magnetically Driven Flows in Arched Plasma Structures. Physical Review Letters, 109(7). 075001.

Zhai, X., & Bellan, P. M. 2016. A hybrid Rayleigh-Taylor-current-driven coupled instability in a magnetohydrodynamically collimated cylindrical plasma with lateral gravity. Physics of Plasmas, 23. 032121.

Changes in research objectives (if any):

Change in AFOSR Program Manager, if any:

Dr. Julie Moses has replaced Dr. Kent Miller

Extensions granted or milestones slipped, if any:

AFOSR LRIR Number

LRIR Title

Reporting Period

Laboratory Task Manager

Program Officer

Research Objectives

Technical Summary

Funding Summary by Cost Category (by FY, $K)

	Starting FY	FY+1	FY+2
Salary			
Equipment/Facilities			
Supplies			
Total			

Report Document

Report Document - Text Analysis

Report Document - Text Analysis

Appendix Documents

2. Thank You

E-mail user

May 06, 2016 16:05:36 Success: Email Sent to: pbellan@caltech.edu